Economic Operation and Control of Power System

Dr. Gururaj Mirle Vishwanath

Department of Electrical Engineering

IIT Kanpur

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Lecture – 37

Hello and good morning everyone. Welcome you all for the NPTEL online course on Economic Cooperation and Control of Power System. So, we will continue our discussion on real time simulation tools and how to use them, the impact of multiple renewable energy sources and key applications where we discuss about you know utilizing this renewable energy converters to address this reactive power requirement of the system during steady state, dynamic and transient state. So today's class we will explore some of the real time simulation toolbox. The first one is RTDS, Real Time Digital Simulator. So there are some features that I have displayed here.

You see the PB5 processor cards are there and the three cards per rack, we call this as rack. You see here this is one rack, this is the second rack. Like this you know at IIT Kanpur we have six racks. So we have six racks here.

So each rack has three cards, PB5 processor cards and then each card contains, I mean is capable of simulating 72 single phase nodes. So the power system nodes and in fact you can also expand it to be to simulated 2 into 72 single phase nodes also, single phase nodes. I hope you understand what is nodes. This means you know I will say if I will just give an example, very simple thing. They say there is a resistance and an inductor between the intersection of any of the elements there always existence of a node.

That means you can see there is a node here right and also let us say we are connecting a voltage source here and there is a let us say load, resistive load and there is a ground right. So how many nodes you can see one can see here? This is node number 1 because this intersection between voltage source and the resistance. This is your node number 2 and there is another node which is node number 3. It is not just there. There is another node here.

This is node number 4. We consider it to be a reference node, ground but that is also a node. So RTDS, the simulation what we develop in RTDS, the analysis is done through nodal analysis. Whereas MATLAB whatever model you do which is a very familiar toolbox and there we go for state space modeling, state space equation we derived, very familiar expressions x dot is equal to Ax plus Bu right, y is equal to Cx plus Du and all these things. X is input variable, state variables, u is the input variable, y is the output variable right.

So MATLAB works with state space analysis whereas RTDS based simulation works with nodal analysis. So there is a dedicated software which is known as RSCAD. So this is a software used to model any real time simulation power system toolbox. So there are set of library blocks which are used from which you can pick up the elements similar to the MATLAB also where you have library and you pick up the elements. In RTDS also there are so many library blocks already there are inbuilt example models also about doubly fed induction generator, DSTATCOM and all these things.

You can just take them for study purpose and you can do the modification in terms of control strategy. Also very widely used popular power system online toolbox is RTDS and this also has PB5 cards possesses 2 input output and 6 communication ports and more importantly this feature helps us to connect to the external hardware. Something called as GTAO, GTAI, GTDO and GTDI cards called as Giga-Transceiver Analog Output, Giga transceiver analog input, Giga transceiver digital output, Giga transceiver digital input cards that means let us say the plant is present outside and the controller is present within the RTDS model that means the PI controller whatever the controller is present. Now a physical hardware prototype is present outside that means let us say there is a microgrid that need to be controlled. So what you do is you need you need to you know sense the signals real time voltage and current signals to pass it to the controller which is sitting within the RTDS and then take out the do the control action, take out the switching pulses and then pass it on to the converters which are controlling this physical hardware devices.

Maybe a PV emulator, maybe a wind emulator and maybe the battery controllers, battery converters, bidirectional converters, boost converter, PV MPPT tracking and all these things. So how do you do it? You can use this GTAI because you need analog input signals, real time analog voltage and current signals. You use the sensor with physical sensors present outside the microgrid and then sense this voltage and current signals, pass it on to the GTAI. RTDS perspective it is analog input, RTDS perspective it is analog input and then you carry out the control performance and then by using GTDO digital output blocks you send you generate the switching pulses and pass it on to the converters. And sometimes you also need GTAO and GTDI cards also, GTAO and GTDI.

So why do you need GTAO? Let us say you want to, you have a voltage source or a grid programmable grid source and you want to generate the voltage as per your desire. It is a controllable voltage source basically. Now within the RTDS model you can have that variable controllable model voltage source and then you scale down the voltage because in RTDS whatever the power system model that you develop the voltage level is in terms of kilovolt by default and the power level will be in terms of megawatt. It is not in watts or volts. So but let us say you have a programmable voltage source of capacity 400 volts.

So what you do is the GT using GTAO ports of course this voltage signals will be in the range of 0 to 5 volts. It is low voltage signals, control signals basically. Now what you can do is you have the voltage source model within the RTDS platform then you can use this GTAO blocks and then you pass on this control signal to this grid source or a grid emulator so that you can generate the voltage varying from 0 to 400 volt and you can carry out multiple actions. So GTAO is has such kind of application. I will discuss in detail also when I go to power hardware loop experimentation and there is something called as GTDI.

Let us say if there is a controller outside and the plant is present within the RTDS platform then you need to generate switching pulses from the outside controller and pass it on to into the controller which is present within the or the converter which are present within the RTDS model. So you need GTDI. So this is another important toolbox and there is something called as GTNET cards, real time communication link to and from the simulator to other hardware software where Ethernet communication can be done. And the next simulation toolbox is Typhoon, Typhoon HIL, Typhoon HIL we say actually. So this is another very powerful simulation toolbox.

So this is very popularly used for microgrid sort of application. You want to you know control a specific microgrid so MATLAB based models. So this is very famous for microgrid control. This also has AI, AO, DI, DO features and detailed converter models are all present. So this is one such simulation toolbox and there is something called as Opal RT.

This is also very popular one. So Opal RT multiple model blocks are there like EFPGASIM block, HyperSIM, E-PhaserSIM. So these are some of the features where EFPGASIM facilitates to carry out power electronics based modelling and also because high switching frequency pulses can be generated. So, Opal RT is very famous for power electronic based controllers because you can generate very high switching frequency. And E-PhaserSIM if you want to you know read the data at RMS and phase angle information need to obtain.

So this can be done by using E-PhaserSIM and this also has AI, AO, DI, DO ports which helps us to connect to any external hardware and carry out the control action. So Opal RT also facilitates power system based modelling but this is very popular for power electronics based applications. Whereas RTDS is very good for power system based application. Of course there is an upgradation and all of them are equally competent enough for multiple applications but they have their own standard toolbox which facilitates either power system or power electronics based modelling. But the good thing is there is something called as Co-simulation.

What we do is you have multiple toolbox like RTDS and Opal RT. The power electronics component can be modelled through Opal RT and power system aspect can be detailed modelling can be done through RTDS based toolbox. Then you can have the advantage of individual toolbox and something called as Co-simulation can be carried out. That means you break down the network, keep the power electronics part in the FPGA SIM which is present in Opel RT, take the power system component, place it in the RTDS based model, then have the interface between them. There are so many interfacing algorithms.

Then enjoy the advantage of the expertise of RTDS and Opal RT. So this is called as Co-simulation. This is also very famous study. Now let me just explain you about what is real time simulation. So this is nothing but simulation taking place corresponding to the real time clock speed.

Let us say I wear a wristwatch and I just watch the time and the simulation also runs within the simulation toolbox synchronized with the clock speed which is present in my watch. So that is what we call it as real time. For example, I have given here if a tank takes 15 minutes to be filled, physical tank taking 15 minutes to be filled, then the real time simulation also should take 15 minutes time. That is what is called as detailed exact modeling. The replica of the physical model, physical system that can be seen in the simulation platform.

So then what you, the inference that you can get is whatever simulation model I have, I can use it to carry out certain analysis which can also be equally validated back in the physical system. The transient studies because I cannot create a fault in the physical system and perform my control action. I have to be ready with the control action and then deployed, validate through simulation, then deploy it in the physical model. So there comes the advantage of real time simulation models. So irrespective of the size of the model, the simulation takes place at the clock speed.

Let us say the network size is just very small, 2 nodes to hundreds of nodes. So the simulation time takes the same. Whereas in the case of MATLAB or other offline tools, as the size of the system increases, the simulation time increases. Naturally you might have seen if you build a very big microgrid setup and this and that, so many complications are there, then it may take hours together, sometimes one day also.

The simulation goes on in MATLAB. But that is not the case in real time simulation toolbox. So it is necessary to model the system in real time platform which helps us to study the real time dynamics. That is the essence. So create those scenarios, practical scenarios, study, develop the algorithm and to ensure that physical system will not get damaged during certain transient events, you prepare yourself during such kind of dynamic events. And if the power system analysis is to be done, then the overall system can be made accessible in one single platform.

The accuracy of the analysis depends on the accuracy of the models in a way. So the overall simulation is modelled at a very small time step making it close to the real time power system components up to 50 microseconds. I am speaking about RTDS. And the power electronics components could be less than 2 microseconds because you need, you know, very low time because the switching frequency is high.

So very less time you require. So even in RTDS also there is something called a small time, small step or substep, substep we also call, nowadays they are also coming with this substep models. So small step and substep models, blocks are present. Within the whole power system network, you keep this small step block and inside this you simulate the power electronics components. So outside the entire power system is simulated at 50 microseconds but within this small step then whatever is the components which are present that are simulated in 2 microseconds. Now I will discuss what is control hardware in the loop.

So what we do here is in the RTDS the plant to be controlled is present. That means as I told here I am simulating the plant. That means there could be a power system network with renewable energy sources connected at different buses or different nodes. Now I use this GTAO port, GTAO port to send out the voltage and current measurements. Let us say there is an inverter that I need to control the output of the inverter, the current.

The current I will sense and I pass on to the external controller and then there is something called as, there is a controller present. Let us say this is a DSP board. There is a controller present. Let us say this is a DSP board or FPGA board whatever. And then there is a control action takes place here.

Then you generate the switching pulses. Switching pulses. And then by using GTDI ports you use these switching pulses either 1 or 0 whatever. Switching pulses and then this is passed on to the model which is present within the RTDS. That means there are converters present here and they would get the switching pulses coming from the outside controller. So this is something called as CHIL, controller control hardware in the loop.

It is a loop, right. It is a real time closed loop control. And then there is something called as hardware in the loop. What we do here is, now the external hardware is present outside. Hardware is present outside and within the RTDS there is a controller present. The plant is present outside, the controller is present within the RTDS platform.

So what we do here is the RTDS receives the current and voltage signals measured through the sensors outside. There are so many sensors which are placed. And the switching pulses are sent out from the RTDS using the GTDO ports. As you see here we are sensing the current signals through GTI, GTAI ports and then we are generating the switching pulses.

We are generating the switching pulses. This is GTDO. You can see here this is GTDO. We are generating the switching pulses and giving, issuing the switching pulses to the converters. You can see here this is a AC-DC hybrid microgrid model.

AC-DC hybrid microgrid hardware testbed. What is there here is, there is a battery, lead acid battery is placed and there is a super capacitor. The combination of lead acid battery and super capacitor we call it as hybrid energy storage system. Hybrid energy storage system because lead acid battery is a high energy density device whereas super capacitor is a high power density device. So combination of them would able to meet out the expectation of the real time system. I mean practical system because high power density means within a short time somebody can inject a good amount of power, expected power.

In a short time somebody can absorb the transient. So this is a transient device basically, transient supporting device whereas the battery, lead acid battery or any battery, lithium battery. So I mean we just use for a steady purpose this lead acid battery. I do not recommend this is a very good device, a storage device. So for steady purpose we have taken it. So anyway whatever may be the storage device, high energy density device is helping us to sustain for a long run during steady state.

Let us say you want to run a bulb for one hour. That is why this rating is in terms of AH. The battery rating is in terms of AH. So much of ampere of load sustained for so much of time, ampere hour, kilowatt hour, something like that. So this is a high power density device, super capacitor is a high. This is nothing but a stack of capacitors compiled together, put up together and they can meet out the expectation very quickly.

So the rating of this super capacitor will be in terms of farads. Usually hardly the filter capacitors are in terms of milli farads, micro farads. But this rating of super capacitor will be in terms of farads, 57 farad, 125 farads like something like this. Now there is a combination of battery and super capacitor and they are connected to a DC bus.

You can see here this is a DC bus. So this is a DC microgrid setup basically. So this is a DC bus and they are connected through bidirectional converters, bidirectional converters. So bidirectional converters means they can help you to either charge or discharge, it is bidirectional. So there is a battery and super capacitor. Let us say, I will discuss about that little bit and then there is something called as PV, photovoltaic.

Either you can connect a physical PV motor system. In this case what we have used is we have used a PV emulator. It will emulate the characteristics of a physical PV system. In fact, it is so handy and comfortable so that you can create some scenarios which may not be happening in the real time system. Let us say you want to create shading and see how during shading also you can control the MPPT or something like that. So you can emulate these characteristics using PV emulator and we have also have, we also have programmable DC load.

Is a programmable PV emulator and programmable DC load. That means you can emulate the characteristics of three varieties of loads basically. Zip load we call it as. Zip means constant impedance, constant current and constant power. So any load that you see in the real time may be categorized into any one of these types, constant impedance, current and power.

Let us say this bulb load. Bulb load is a constant impedance load. The impedance is fixed. So if there is high voltage, there is a current corresponding to that. Impedance is fixed. So that is, that characteristics can be emulated through this programmable electronic load.

That means you can also program it at what time I am going to switch on this specific load. What is the change in power, change in the impedance, change in the current that can be emulated there. Now all of them put together are connected to a DC bus, two wire DC bus. And then what happens is, let us say this DC microgrid is operated in a isolated fashion.

They are not connected to any external system. They are independent on themselves. That is what is microgrid means. Microgrid means they have their own energy source, they have their own load, they have their own storage component. They are independent, they can independently sustain even if they are not connected to the infinite grid. So let us say if they are operating in an isolated fashion, what happens? The controller within the RTDS would design in such a way that it would sense the voltage and current signal.

It would sense the voltage signal of the DC bus and the current signals of this PV emulator and through the sensors, we can sense the current of the, current flowing through this bidirectional converters as well as the boost converter which is interfacing between PV emulator and the DC bus. These current signals are sensed and they pass it on to the RTDS, the PI controller which is present in the RTDS mode. Now the control loop during isolated mode works in such a way that it would direct this battery and super capacitor to either charge or discharge even if there is a change in PV power output or change in load pattern such that the DC bus voltage would remain constant. So any healthy operation means even if there is a load switching in this, there is a generation changes, load changes, the bus voltage should remain steady.

That is what we see in also in real time system. Let us say switch on this light or switch on the fan, switch on the AC, we do not see the change in voltage, we do not see the change in frequency. We want to have a steady voltage and frequency irrespective of there is a change in load. Similarly if there is a roof top solar and I am injecting power to the system, distribution system, I do not want to see any change in voltage profile because I am injecting the power. That is why we call it as infinite grid. So practically what we are doing is we are trying to mimic the characteristics or the features of the infinite grid through the small players of battery and super capacitor.

So because they have this ability to charge and discharge, let us say if there is a lack of power in the system, PV irradiation is very less, PV irradiation is very less and there is a high load. PV irradiation is very less and there is a high load. That means there is a lack of power in the system and if you continue to allow it, the bus voltage would keep on decreasing. So what you want to expect is there is a storage device which is present.

It has charge within it. Let us utilize the charge to meet out the expectation of the system. That means they will start discharging to maintain the voltage profile constant. Similarly the opposite way. If there is a high PV irradiation, low load, I mean taking an extreme condition, that means there is surplus amount of power which is present within the system. So what do you want to do is let us utilize that and store it within this battery so that it can be used during the situation when there is a lack of power from the solar.

So that is what is also expected in future power system. That is why storage plays a very crucial role because we are totally moving towards greener energy. We need to have a storage device which can help us to adjust with the dynamics created by this renewable energy sources. Now this DC bus here is connected to, I mean we have considered one sort of wind system which is called a double fed induction generator which has a back to back converter and all these things. We have connected here at the DC bus of this, between the rotor side converter and the grid side converter there is a DC bus.

So we are connecting here to DC bus. This is a specific topology and then the AC output of a double fed induction generator is connected to the power amplifier. This is behaving like a grid emulator. That means I told there is a programmable voltage source, grid source. So what we are doing is we are using GTAO port of RTDS and we are generating some voltage and at the power amplifier terminals on the grid voltage source terminal it is generating the voltage as I command from the RTDS. So to this ports I am connecting this DFIG system which is producing power in AC fashion.

It is a AC source basically and to that DFIG I am also interfacing this DC microgrid which has PV, battery, super capacitor and programmable source. So the whole the system put together is ultimately being connected to the RTDS. So this is one of the application of RTDS. This ability to have hardware in the loop experimentation.

So it is a closed loop control. Next moving ahead we will discuss about power hardware in the loop experimentation. We call it as PHIL. So first level of validation is real time simulation model. Then we go for control hardware in the loop where plant is kept within the real time simulation and control is kept outside and then we moved ahead to the hardware in the loop where it is just opposite around where the plant is present outside and the control is present within the real time simulation tool box and here we call it as power hardware in the loop.

So this is you know one step which says steady is close to actual field validation. Just one step closer to the far away from the real time field validation. So here what we do is part of the system is present in the RTDS and part of the system is present in the hardware. In the entire plant part of the plant is present in the RTDS and one component of let us say in simulation you did the entire plant was present within the simulation. Now you take out one specific renewable energy source or a microgrid whatever you take it out and replace that with a physical hardware.

So here in this case I am showing with the double fed induction generator. So there is a 33 bus distribution system. Earlier the entire DFIG was also present seen in the 33 bus distribution system. Now what I have done is I have just pulled out that DFIG, removed that from the simulation model and I am connecting a physical DFIG and what I am doing is I am placing a power amplifier in between. This bridges a gap between a simulation tool box which is working in control signal level and there is a power signal level real power based hardware setup which is present outside.

It bridges that gap. So what it does is we use something called as ideal transformation method. What we do is we scale down the voltage from RTDS and pass it on to the because RTDS as I already told it works in kilovolt. You cannot have a physical kilovolt programmable voltage source present. So it will be in terms of 230 or 400 volts whatever. So you scale down the voltage, give it to the power amplifier and then return if there is a DFIG which is present, this is working in terms of amps.

Let us say the rating of this DFIG is 2.2 kilowatt. I am just giving an example. So if there is a 2.2 kilowatt based double fed induction generator, let us say it is putting a 230 volt then you may get 10 amps or 12 amps, 13 amps whatever may be the current. So this is in terms of amps. But back in the RTDS platform, the system is working in megawatt that means kilovolt into kilo amps.

That is why you get megawatt right. Kilovolt into kilo amps. Anyway this voltage level is already in kilovolts. But you cannot just pass on the signal which is in terms of amps. So what I do is I will scale it up, scale it up in terms of 1000. So then I will get, even though if there is a 5 amp current which is actually flowing through in the physical system, so inside it looks like a 5 kilo amps.

So from RTDS perspective, RTDS would feel the entire system is present within the RTDS model. Now it feels like a megawatt, DFIG is connected to it. Though it is 2.2 kilowatt, maybe from the RTDS perspective it looks like a 2.1 megawatt or 2.2 megawatts. And whereas the physical hardware perspective, it would feel like you know it is connected to a low voltage based system. So by this the advantage that one gain is there is a physical dynamics that is happening in the DFIG because it is a hardware component. And that can, I can reflect this dynamics back to the simulation model. So that I can bring the simulation model closer to the field level study.

So this makes it more realistic for our understanding. And there is a communication delay also which is incurred because you pass on the signal, the voltage signal and there is a control signal delay which is happening. That is also a realistic approach because within everything is present within the simulation model, the delay component may not be realistic. You assume everything is present there itself, but that is not the realistic scenario.

So this is very important study. It helps us to carry out bi-directional analysis. That means if there is a fault present in the real physical system, power system model which is simulated in the RTDS platform, if there is a fault then how my DFIG which is a hardware based physical hardware prototype, how it would respond to that fault. The fault analysis can be carried out. The impact of the system, fault on the system, the impact on the real physical hardware prototype and bi-directional also. If there is a change in wind gust, wind directions because it is a wind emulator, I can change the wind, I can physically emulate the characteristics of a physical wind plant. So if there is a change in wind directions or the dynamics due to the renewable energy sources and how it would impact back to the system.

So the bi-directional analysis can be more realistically studied through this power hardware loop experimentation. So I will just give you an overview about coordinate voltage control scheme for the distribution system and then we will discuss in the next class about its detailed applications. So you see here, we have considered IEEE 33 bus distribution system for the study where there is a utility grid and there is the, it is a radial network basically. You are very familiar with two types of distribution networks.

One is radial network and there is a mesh network or ring network. So though we prefer mesh network, so often we see system also has radial, in conventional system everything was radial basically. So in the radial system the biggest disadvantage that one can see is the far away bus, let us say there is 18 bus. The voltage profile will be very poor as compared to the bus which is closer to the upstream source. This is upstream bus basically.

One bus number one is upstream bus, there is a downstream bus basically, last bus. So the voltage profile is uneven throughout the distribution network and we have considered the DSTATCOM. I have already discussed in my previous class what is DSTATCOM. It helps us to inject reactive power and absorb reactive power in a very quick manner and there is also doubly fed induction generator which is connected and there is a DC microgrid. I discussed about DC microgrid which consists of battery and load and PV.

So DC is connected through the inverter to one of the buses here. The entire system is built in a RTDS platform. That is why you see the capacities in terms of megawatt and voltages in terms of kilovolt. So and there is a onload tap changer transformer, OLTC which is present within the system. This helps to you know meet, if there is a change in load it would try to retain the voltage back to the nominal value.

So this has plus or minus 16 steps because the voltage profile changes in terms of steps here. Plus or minus 16 and the operating voltage range we have considered is 0.9 to 1.1 per unit. Plus or minus 16 means 1, 1 per unit is the nominal value.You expect the voltage profile should be at 1 per unit and below 1 and above 1. If the voltage goes below 1, 10 percentage that means 0.9 per unit and above 1, 10 percentage higher due to any reason that is 1.1 per unit. So then during this let us say if the voltage is below 1, it is operating at 0.9 per unit. Then you need to increase the steps, increase the taps such that the voltage would increase that means plus 16 steps will be helpful. If the voltage is now let us say extreme upper hand, upper limit which is 1.1 per unit then use this minus 16 steps that means you low down the steps. Already it is situated at some point, you decrease the steps such that now voltage would come to 1 per unit.

That means each step would change the voltage by 0.00625 per unit. Just divide 0.1 by 16 or 0.2 by 32, you would get this number 0.00625 per unit change in the voltage. And this converters DSTATCOM, doubly fed induction generator and the inverter which is associated with this DC microgrid, they would not change the voltage in terms of steps. They would not change the voltage with the reactive power injection in terms of steps.

It would be like a linear rise, linear rise in the output change. So now you have multiple combination and OLTC has its own time constraint before it operates. It does not operate in steady state. Of course in this study we have considered electronic OLTC. It is not mechanically operated OLTC but yet the simulation time would be in terms of 625 millisecond or something like that. So actually the mechanically operated OLTC would take more time in terms of seconds, 10 seconds, 12 seconds and there is also limitation in terms of how many steps that you can operate.

Hardly in a year you would not expect the change in the operation of OLTC, mechanically operated OLTC more than 10 or 12 or 15 times. So it does not happen very frequently. But here we have considered electronic OLTC so there is no limitation in terms of how many steps that I can operate but yet there is a time duration it takes before it operates which is in terms of 625 millisecond because you do not want to see the frequent change in the steps here also.

Otherwise it keeps on changing the voltage profile. So that is the reason. So this is one thing. And now having this combination compared to this DSTATCOM and DFAG and this converters, the time taken by voltage is significantly higher because this fast acting converters very quickly can inject reactive power. So there is a combination of slow acting device and there is a combination of fast acting converters. Having this combination of multiple voltage regulating devices, having different speed of response owing to any perturbation or disturbance in the voltage profile of the system, how do you manage them very effectively such that you would have an improved voltage profile in the system during steady state operation, better reactive power reserve, have a good transient response. So multiple benefits can be, objectives can be met out and loss minimization can be also another objective.

So this is one such classical study. So we will discuss in detail. I just described the system. We will discuss what are the control algorithms that we have developed and how RTDS can really play a very key role to realize such kind of implementation of control strategies. With this I will conclude. Thank you very much.